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Tensile Strength, Extensibility, and Other Characteristics of Wheat Roots in Relation to Winter Injury

C. A. Lamb

OHIO
AGRICULTURAL EXPERIMENT STATION
Wooster, Ohio

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TENSILE STRENGTH, EXTENSIBILITY, AND OTHER CHARACTERISTICS OF WHEAT ROOTS IN RELATION TO WINTER INJURY[1]

C. A. LAMB[2]

INTRODUCTION

The most important problem in wheat growing in Ohio is control of winter injury. Statistics show that, over the past 35 years, farmers of this State have plowed up in the spring, on the average, approximately 10 per cent of the acreage seeded the previous fall. This was done because it was so badly damaged that no paying crop could be harvested (12).[3] The abandonment amounted to a little less than 200,000 acres each year. At 15 bushels per acre, it represents 3,000,000 bushels with a market value of $2,400,000, at 80 cents per bushel. Even this large sum does not include all the damage, for yields are affected to a greater or lesser extent on many fields that are not abandoned. Reducing this loss is, therefore, a problem of great practical importance.

Winter hardiness of wheat varieties, or the ability of these winter annuals to survive the dormant season, is often loosely considered as synonymous with cold resistance. It has for a long time been recognized, however, that winter injury may be due to secondary effects of low temperature, such as smothering under ice or tightly packed snow or upheaval of the plants due to alternate freezing and thawing. Salmon (9) has analyzed very clearly the causes of damage to fall-sown cereals.

In the Soft Wheat Belt of the northeastern United States, it is only in exceptional seasons that winter wheat is killed by the direct effects of low temperature. In the opinion of workers long associated with this area, the most common cause of injury is probably heaving; that is, the pulling of the plants from the soil when the surface is raised up by frost action. This damage is most likely to occur in early spring.

Heaving of soil is not a simple physical process due to the change of soil water from the liquid to the solid state. Münichsdorfer (6) gives an excellent review of the mechanics of heaving and the conditions necessary to its occurrence. Provided the soil freezes without layers of ice separating out, increase in volume seldom exceeds 5 per cent. With severe heaving, however, the surface of the soil may be raised as much as 60 per cent of the depth of the frozen layer.

In order that this may occur, certain specific conditions must be present. First, the soil particles must not be too large, as in coarse sands, nor too small, as in very heavy clays, but must be of such size that there is good capillary movement of water. Second, the surface soil must be nearly saturated and

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[1]Submitted as a thesis for the degree of Doctor of Philosophy at Cornell University. 1935.

[2]Acknowledgments.—The author wishes to express his sincere thanks to Dr. L. Knudson, Department of Plant Physiology, for helpful suggestions in the course of these studies and to Dr. Knudson and to Dr. O. F. Curtis, of the same Department, for reading the manuscript. He also wishes to acknowledge the courtesy extended by the Ohio Agricultural Experiment Station in permitting the investigation to be used as thesis material.

[3]Numbers refer to literature cited.

there must be capillary connection with rather large reserves of water, such as a high ground water table. Finally, the rate of freezing must be such that pure ice layers may separate out in the soil.

When the above conditions are met and freezing occurs, the water in the surface soil changes to ice. This removes the liquid phase from the soil-water system, and water moves up from below to the bottom of the frozen layer. Then, as the heat loss from the surface continues, an ice layer forms. If the heat loss is so rapid that water cannot move quickly enough under capillary forces to build up the ice layer but freezes in the soil mass below, heaving does not take place. However, with a reasonably constant air temperature and with rate of heat loss decreasing as the depth of the frozen crust increases, a point will commonly be reached where an ice layer will separate out. Thus, conditions necessary for heaving are not very critical. Very often more than one ice layer develops; in fact, a number are commonly found of varying thickness and with layers of frozen soil between.

The raising of the soil surface is almost entirely due to the ice layers and is practically equal to the sum of the thicknesses of such layers as exist. The water that freezes out in this way as a separate phase is mainly water which was not originally present in the more or less saturated surface soil but was drawn by capillary forces from the ground water table or other relatively large source of supply. Therefore, when thawing occurs, there is present at the surface of the soil a large amount of water. This accounts for "creeping" of soils down hillsides and breakdown of country roads and also is a factor in increasing the liability of crop damage from heaving when there is a period of alternate freezing and thawing, usually a diurnal cycle.

Injury to the wheat plants results because, in the initial stages of freezing, the crowns of the plants become firmly embedded in the frozen surface soil. As the ice layers form and this surface is raised, the plants are literally pulled from the ground. This may break some of the roots, or, in any case, when the soil thaws out and subsides, they are left exposed to the air. Repeated freezing and thawing in very severe cases may force the plants almost entirely out of the ground.

When soil moisture conditions or rate of freezing may be such that little or no heaving occurs, the volume changes involved when the soil freezes and thaws subject the roots to quite significant, though seldom serious, stresses.

Two methods of control of heaving injury present themselves. In the first place, the environment in which the crop grows can be improved to avoid, insofar as possible, conditions which favor damage. Thus, good drainage will help to keep the ground water table lower and the moisture content of the surface soil below the point where severe heaving will occur. Also, relatively early planting in a well-prepared and adequately fertilized seedbed will insure strong, healthy plants which in themselves are less liable to injury. Abundant foliage probably has a marked effect in retarding the rate at which the soil about the crowns of the plants freezes and thaws. The second approach to the problem lies in the isolation of new varieties more resistant to heaving injury than those now grown. It is with this second method of attack that this study is particularly concerned.

Observation of wheat nursery and variety test plots by experiment station workers in the northeastern section of the country indicates that, without question, injury from heaving is not the same for all varieties. Some are forced out of the ground more readily than others, and the roots of some varieties appear to break more easily. The fundamental question then arises as to what are the characteristics which enable one variety to survive the stresses of alternate freezing and thawing better than another. It would seem obvious that important differences must lie in the root systems.

A review of the literature reveals that very little work has been done upon the specific differences between the roots of different varieties of wheat or other winter cereals. One paper by Kokkonen (4) is directly concerned with the problem. Working with winter rye, he found a definite association between the tensile strength and extensibility of the roots and winter survival in Finland. From his paper, it is evident that injury under the conditions he studied was at least in part due to root damage from stresses of freezing and thawing.

On first thought, the strength of the roots would seem to have little possible significance. The forces involved in the formation of ice are so great that even the strongest roots could have but negligible powers of resistance. However, when it is remembered that these roots may also stretch in some measure and thus exert a continuous force while the ice layers are forming and, further, that the hold of the frozen soil surface on the crown of the plant may not be sufficient to break strong roots, the importance of this factor becomes evident. The ability of the roots to stretch without breaking may in itself be important.

The forces necessary to prevent the formation of ice layers in a soil are large but by no means in a class with those necessary to prevent water changing to ice. The formation of an ice layer implies the presence of a liquid film of water on the lower surface of the frozen layer and intimate contact of this film with the capillary water. Pressure applied to the soil surface is transferred through the frozen layer to the soil structure below but not to the liquid water in this unfrozen region. The water in the soil capillaries below must undercool before it can freeze to the ice layer, for in so doing it must lift the surface soil. Water in capillary tubes can be undercooled the more readily the smaller the tube, and water in the capillary pores of the soil behaves in entirely analogous fashion. Taber (10) found that a pressure of 15 kg./cm.^{2} would stop heaving in any soil he studied. At this pressure, freezing always occurred in the capillary pores and no ice layers formed, even in very fine textured soils.

It was decided, therefore, that a study of the tensile or breaking strength of wheat roots, together with a record of the amount of stretch at the breaking tension, might be of value as a step toward the evolution of some empirical technique for isolating lines resistant to heaving damage, similar in usefulness to the cold chamber as a means of selecting cold-resistant varieties.

This paper presents the results of preliminary studies on the size, breaking tension, and extensibility of the roots of 15 varieties of winter wheat. The data are analyzed in an effort to correlate winter behavior with the physical measurements and thus indicate a basis upon which the plant breeder can discard undesirable lines early in the breeding program and with greater assurance that valuable material is not being lost.

MATERIALS AND METHODS

Ranking of wheat varieties according to their resistance to heaving damage has never been seriously attempted. Neither has it been determined what is the most common way in which heaving injures the plants. In some cases it is root breakage whereas in others drying winds wither the exposed roots and thus cut off the water supply.

Realizing this lack of fundamental information, Dr. S. C. Salmon, Principal Agronomist in charge of Wheat Investigations, Bureau of Plant Industry, United States Department of Agriculture, instituted in 1932 a cooperative nursery project with the experiment stations of the soft winter wheat area in the northeastern United States. The Eastern Uniform Winterhardiness Nursery was planted that fall at 23 locations in this region. It included 30 varieties, mainly sorts of commercial importance in the area, together with a few varieties from the similarly conducted nurseries of the Great Plains. The object was to answer the very important questions outlined above. This project is still being carried on, with practically no change in the list of varieties or locations.

In order to make the fullest use of the Uniform Nursery results, the varieties for this study were all chosen from those included in it. Choice was made with two objects in view: first, to include a wide range insofar as winter reaction was concerned and, second, to include varieties developed in several distinct areas. This was done so that any correlations or associations which might be present would be clearly evident. The following groups were selected on this basis:

(1) **Minhardi** and **Kharkov.** These varieties are definitely cold-resistant and well adapted to the Great Plains area. Minhardi was developed at the Minnesota Station while Kharkov was introduced from Russia many years ago and is widely grown in the hard winter wheat belt.

(2) **Purkof** and **Purdue No. 1.** These wheats were developed at the Indiana Station. Purkof was released a number of years ago in response to the millers' demand for a bread wheat. Purdue No. 1 is a new selection extensively tested in Indiana and adjoining states. It is a soft wheat of the type desired by the miller in Indiana today.

(3) **Red Rock.** This is a Michigan variety and is the most popular soft red wheat in that state, where it is grown mainly on the heavier soil types.

(4) **Trumbull, Fulhio, Nabob,** and **Gladden.** These four varieties were selected at the Ohio Experiment Station at Wooster. Trumbull is now the third ranking soft red winter wheat in the United States. Trumbull and Fulhio together make up approximately 75 per cent of Ohio's wheat crop. Nabob and Gladden are not so extensively grown, but there is ample evidence of their reaction to winter conditions.

(5) **Nittany.** This is a Pennsylvania Station introduction, well adapted to large areas of that State. It is also known as Penn. No. 44.

(6) **Valprize.** This variety was introduced by the Department of Plant Breeding, Cornell University, at which institution it was developed. It is reputedly resistant to heaving damage in New York State.

(7) **Fulcaster, Poole, Harvest Queen,** and **Purplestraw.** These wheats represent the older varieties of soft red winter wheat grown in the eastern United States. They show considerable range in their resistance to winter injury of various types.

Experimental work was started on this project in the spring of 1934. The first problem was to devise an apparatus which would measure the breaking tension and extensibility of the roots. Since Kokkonen's paper was not available at this time, it was necessary to develop apparatus and technique independently. The fundamental principles of the first apparatus, constructed at Wooster in February 1934, are shown in Figure 1.

The apparatus was essentially a balance beam with fulcrum at F. A complete bicycle front axle assembly was used and proved entirely satisfactory. It was very sensitive under considerable load. The two ends of the beam were of unequal length. On the short end, 12 inches from the fulcrum, a clamp (C_1) was attached. This was lined with a rubber material, used in steam packing, which was moderately hard and had slightly roughened faces. Each clamp was closed by wing nuts on two ¼-inch carriage bolts. A second clamp (C_2) of identical design was attached to the base in such a manner that it could be adjusted for the length of root section used. A post (S) stopped the beam at the horizontal position. This obviated the necessity of measuring each section stretched. A bucket (B) was hung from the long end of the beam 12 inches from the fulcrum. Water was run into this bucket at a constant rate from a siphon. The tension on the root, therefore, was exactly equal to the weight of water in the bucket at any time. The beam was exactly balanced by a counterweight (W) when the bucket was empty.

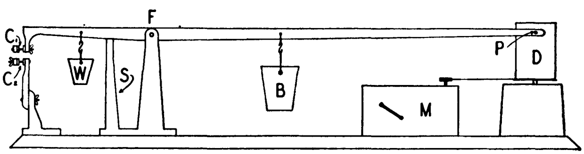

Fig. 1.—Original apparatus developed for determining breaking strength and extensibility of wheat roots

A recording thermometer drum (D) was driven by a gramophone motor (M) equipped with a speed regulator and so adjusted that the surface speed of the drum was constant and passed the required linear distance each minute. Suitable graph paper, accurately cross ruled, was attached to the drum. A pencil (P) traced a line on the paper from which the desired data could be calculated. Water ran into the bucket at 200 grams per minute, so that each unit of horizontal travel represented a fixed increase in the tension on the root. Each unit of vertical travel corresponded to one-third unit stretch since the pencil (P) was 36 inches from the fulcrum. A mark was made on the graph to indicate the position when water began to flow into the bucket, and the end point was sharply defined since the beam dropped suddenly when the root broke.

Results obtained with this device were very satisfactory, the only difficulty being the necessity for two workers if any speed was to be made. Between determinations, it was necessary to remove the broken root and put in a new one, empty the bucket, wind up the gramophone motor, and change the graph paper. A second machine was, therefore, developed in the spring of 1935 in order to reduce the number of manipulations. This is shown in Figure 2. The advantages are that no graph paper is necessary since direct readings can be made after the root has broken, and the clamps, operated by cams, can be adjusted much more rapidly.

The corresponding letters in Figure 2 designate the same structures as in Figure 1. An electric clock (K) replaces the spring motor and drum of the first apparatus. The second hand gives a measure of the tension on the root as the water flows into the bucket. The pointer (I) indicates the stretch. It is delicately balanced and swings slowly upward if free. The rod (D) carries a pin which limits the swing of the pointer up to the instant the root breaks.

When the break occurs, the rod (D) drops suddenly to the rest (G), which is so arranged that when struck in this manner it stops the clock (K) and locks the pointer (I) in whatever position it may be. If properly adjusted, the movement of this pointer from the instant the root breaks until the rod (D) strikes the rest (G) is negligible. The lag in the clock is constant at about one second after the current is cut off. Thus, after the root breaks, the breaking tension and stretch can be read directly from the clock dial and the pointer scale.

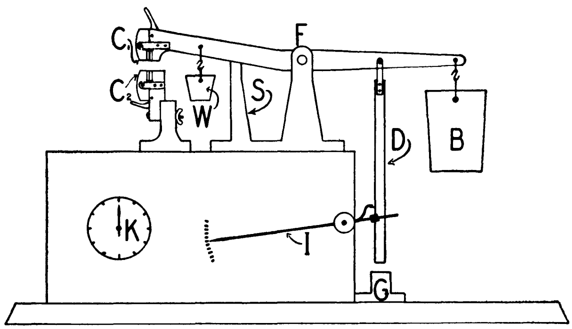

Fig. 2.—Second apparatus developed for determination of breaking tension and extensibility of wheat roots

A cursory examination of the roots of a few wheat plants indicated that probably the best region in which to work would be rather close to the stem end. On the other hand, it was necessary to have sufficient root left at the stem end to afford a satisfactory hold in the clamp. Therefore, it was decided to set the upper limit of the section to be stretched at 1 centimeter from the stem end. This, it later appeared, was the same upper limit used by Kokkonen in his work. The next question was what length of section to stretch, and a 2-centimeter section was arbitrarily chosen; this again was later found to agree with Kokkonen. However, with the wheat root system, this length did not prove satisfactory. The roots lost strength rather rapidly with increasing distance from the stem and careful observation showed that breakage usually occurred in the 2-3 centimeter range and seldom in the upper half of the section. Further, it appeared that the 2-3 centimeter range was stretched to its limit and broke before the 1-2 centimeter region had a chance to demonstrate its true extensibility. This is borne out by the data presented in Table 1, which shows the stretch at breaking tension in per cent of original length of test section for three varieties on which trials were run, using both the 1-2 centimeter and 1-3 centimeter range.

In view of these considerations, it was decided that a 2-centimeter section was too long. Since graph paper was available ruled in 1/10-inch squares and since ½ inch is 1.27 centimeters, this length was used for all the series run on the first apparatus. One-centimeter sections were used on the second apparatus.

Varieties were dug in the field, enough soil being retained to include at least 10 centimeters of the roots. This soil was carefully washed from the roots shortly before the tests were to be made. Plants were then selected reasonably near the mean for the group insofar as size and apparent development were concerned. No attempt was made, however, to select for too great uniformity but rather to include the range of natural variability found. In this way the possibility of setting up artificial differences between varieties was avoided. Errors are larger than if more rigid standards had been used, but it was felt that the results were more significant in indicating that real differences occur under field conditions.

TABLE 1.—Stretch at Breaking Tension in Per Cent of Original Length of Test Section for Three Winter Wheat Varieties

Variety	Per cent stretch at breaking tension	
	1-3 cm. section	1-2 cm. section
Fulhio	34.0 (n = 25)	39.1 (n = 125)
Minhardi	28.2 (n = 25)	35.4 (n = 125)
Harvest Queen	28.3 (n = 25)	32.0 (n = 30)

From each plant selected, one or at most two roots were cut close to the stem with a sharp penknife. Choice of roots was made on the basis of the best developed on the plant. These roots were kept in water up to the time the actual test was run. Just before placing a root in the apparatus, the diameter was determined under a low power microscope with micrometer eyepiece. While measurements were being made the root was kept in water in a shallow petrie dish. The diameter was taken in the region 1 to 2.27 centimeters from the stem and the minimum recorded. From this figure was later calculated the diameter to the nearest 0.01 millimeter and the cross sectional area to the nearest 0.01 square millimeter. Breaking tension and stretch were added to this record, and finally the breaking tension per square millimeter of cross sectional area calculated. All data were compiled in this way.

A number of series were run. The first of these, designated as the H Series, consisted of plants grown in the border rows of the Eastern Uniform Winterhardiness Nursery at Wooster in 1933-1934. The work was done during March and the first week of April 1934. Thus, the material had passed through the winter but had made little or no spring growth. This trial series indicated the probable significance of such a test and it was felt more extensive work was justified.

Weather conditions vary greatly from season to season and between locations in a given season. Wheat makes good growth one year and poor growth another. Therefore, the results of a single year's test may not apply in general. It was felt that, in order to test the validity of any association which might appear to exist between the characteristics studied and winter behavior, a rather wide range of conditions should be included in the studies. With this object, three more series, each including the full 15 varieties noted earlier in this paper, were planned.

One of these, the S Series, was sown in the Oat Nursery at Wooster in the spring of 1934. Two tests were run on the roots of this planting—the first when the plants were only 3-4 weeks old and the second 5-6 weeks later. The first of these trials was made with the seedling roots and the second on the permanent roots of the plants. They are designated as the S and 2S Series, respectively, in the records. Pressure of other work made it impossible to complete the 2S Series at one time and the plants died as a result of the hot summer weather before the tests could be made; this accounts for the incomplete results.

In the fall of 1934, the same 15 varieties were sown in the winter wheat nursery at the Ohio Agricultural Experiment Station at Wooster and also, with the cooperation of the Plant Breeding Department, in the Cornell University Nursery at Ithaca, New York. Two tests were run on each of these series—one in the fall when growth had practically ceased but before any great amount of soil freezing had occurred and the other in the spring after danger of heaving damage was over but before active growth had proceeded very far. It was hoped the roots would not have made any appreciable growth between the two tests and that any changes in their behavior could be ascribed to the effect of winter upon them. The series grown at Wooster was designated W; that grown at Cornell, C. Spring tests were denoted 2W and 2C, respectively.

EXPERIMENTAL DATA AND DISCUSSION

SIZE OF ROOT

Cross sectional area was used as the measure of root size, since it would seem more logically to stand in linear relationship to breaking tension than would diameter. In Table 2, these data are presented for all the principal studies made. The mean cross sectional area in square millimeters is given, together with its standard error. The standard deviation is included to facilitate comparisons, and the number of roots used in each test is indicated.

Size of root varied widely from one variety to another. The most significant data on this point are found in the W and C Series. Root size measured in the spring is less reliable, since the stresses encountered during the winter lead to greater or less damage to the cortical region with consequent increased variability in the data collected.

It is evident from a comparison of the results of root measurements in these two series that all varieties made greater growth at Ithaca than at Wooster. Since seed from the same lots was used for both plantings, differences are to be ascribed entirely to effect of soil and season—that is to say, to differences in environment. Comparison of the weather data at the two stations during the fall largely explains the differences found.

The Ithaca test was sown September 14, 1934. A heavy rain followed planting, and, in general, conditions were very favorable through the late fall. Plants made excellent growth and entered the winter with abundant foliage. Samples were dug about the middle of November and taken to Wooster where the tests were run. The data represent growth under practically optimum conditions.

Wheat is sown later in Ohio than in New York. Date of sowing trials conducted at Wooster indicate that highest yields are obtained when planting is done toward the end of September (1). Moreover, to avoid severe damage from Hessian fly, September 25 is set by entomologists as the earliest safe date for seeding wheat in the vicinity of Wooster. Nursery plantings were begun September 25, 1934, but a heavy rain September 26-27 held up this work for 3 days. The plots for root tests were sown October 3. The rain September 26 was the only precipitation of any account during September and October, and fall growth, which continued into November, definitely suffered from lack of moisture. Conditions at Wooster were much less favorable than at Ithaca.

The rank of varieties is not the same for the two plantings. Figure 3 shows the cross sectional area of roots at Wooster plotted against the same data from Ithaca (W and C Series). The larger errors for the Cornell Series are due almost entirely, if not altogether, to the smaller values of n (50 for the C, 100 for the W Series), as may be seen by comparing the standard deviations.

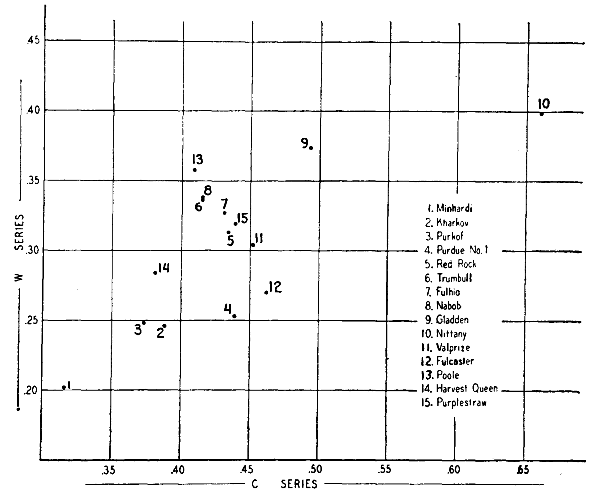

Fig. 3.—Cross sectional area of roots of 15 winter wheat varieties showing correlation of results from C and W Series

In both series Minhardi, Kharkov, and Purkof, all definitely cold-resistant wheats, had small roots. Gladden and Nittany, at the other extreme, had distinctly large roots. At Wooster, where fall growing conditions were not good, the remaining varieties showed some significant differences in root size. At Ithaca, however, where wheat had an excellent start, the differences were much less marked. When given sufficient time and favorable weather, these varieties tend to reach much more nearly the same root size; whereas, under the adverse conditions at Wooster, some developed well while others did not. The performance cannot be entirely explained purely as the result of slower development at Wooster, however, since the change in rank of varieties is in several cases quite marked. Ranking of varieties as to root size in any one test would, therefore, appear to be subject to some error.

Root size is probably a rough measure of the amount of growth made. In both series, it would seem to show a rather definite negative association with cold resistance. The most cold-resistant variety, Minhardi, had distinctly the smallest roots. Kharkov, Purkof, and, to a lesser extent, Purdue No. 1 and Harvest Queen are definitely resistant to the direct effects of low temperature. Thus, it would seem reasonable to conclude that small sized roots are indicative of cold resistance. The converse, however, does not necessarily hold and large roots do not indicate clearly a lack of cold resistance. Gladden, for example, is reasonably resistant to low temperatures, outranking Trumbull or Red Rock in this respect.

TABLE 2.—Mean Cross Sectional Area of Roots of Winter Wheat Varieties (Square Millimeters)*

Variety	Series H	Series S	Series 2S	Series W	Series 2 W	Series C	Series 2C
Minhardi	0.107±0.004 σ=0.043 n=125	0.171±0.002 σ=0.010 n=25		0.202±0.006 σ=0.060 n=100	0.124±0.009 σ=0.061 n=50	0.316±0.010 σ=0.071 n=50	0.260±0.008 σ=0.058 n=50
Kharkov		0.092±0.007 σ=0.036 n=25		0.246±0.006 σ=0.059 n=100	0.166±0.009 σ=0.061 n=50	0.388±0.012 σ=0.085 n=50	0.285±0.011 σ=0.075 n=50
Purkof	0.127±0.009 σ=0.047 n=30	0.160±0.007 σ=0.033 n=25		0.248±0.006 σ=0.056 n=100	0.168±0.006 σ=0.041 n=50	0.373±0.010 σ=0.074 n=50	0.307±0.010 σ=0.069 n=50
Purdue No. 1		0.122±0.008 σ=0.042 n=25		0.253±0.005 σ=0.050 n=100	0.190±0.008 σ=0.059 n=50	0.439±0.007 σ=0.047 n=50	0.293±0.009 σ=0.062 n=50
Red Rock	0.188±0.012 σ=0.061 n=25	0.170±0.008 σ=0.042 n=25	0.459±0.022 σ=0.109 n=25	0.313±0.006 σ=0.064 n=100	0.249±0.007 σ=0.049 n=50	0.434±0.011 σ=0.102 n=89	0.333±0.013 σ=0.089 n=50
Trumbull		0.182±0.009 σ=0.047 n=25	0.475±0.025 σ=0.125 n=25	0.336±0.009 σ=0.087 n=100	0.242±0.008 σ=0.059 n=50	0.415±0.013 σ=0.091 n=50	0.326±0.011 σ=0.081 n=50
Fulhio	0.163±0.005 σ=0.059 n=125	0.171±0.008 σ=0.042 n=25	0.459±0.020 σ=0.102 n=25	0.327±0.008 σ=0.075 n=100	0.276±0.010 σ=0.069 n=50	0.431±0.011 σ=0.076 n=50	0.329±0.011 σ=0.077 n=50
Fulhio (Pure Line)				0.293±0.007 σ=0.069 n=100	0.243±0.009 σ=0.064 n=50		

*All errors are standard errors.

TABLE 2.—Mean Cross Sectional Area of Roots of Winter Wheat Varieties (Square Millimeters)*—Continued

Variety	Series H	Series S	Series 2S	Series W	Series 2W	Series C	Series 2C
Nabob	......	0.211±0.014 σ=0.068 n=25	0.471±0.020 σ=0.098 n=25	0.338±0.007 σ=0.068 n=100	0.258±0.007 σ=0.053 n=50	0.415±0.008 σ=0.059 n=50	0.283±0.011 σ=0.075 n=50
Gladden	0.204±0.006 σ=0.070 n=125	0.170±0.010 σ=0.049 n=25	0.514±0.017 σ=0.087 n=25	0.374±0.007 σ=0.073 n=100	0.313±0.011 σ=0.077 n=50	0.493±0.009 σ=0.061 n=50	0.375±0.011 σ=0.080 n=50
Nittany	......	0.141±0.006 σ=0.032 n=25	......	0.399±0.008 σ=0.079 n=100	0.346±0.013 σ=0.093 n=50	0.660±0.022 σ=0.165 n=57	0.454±0.015 σ=0.109 n=50
Valprize	0.174±0.011 σ=0.057 n=25	0.160±0.008 σ=0.040 n=25	......	0.304±0.006 σ=0.059 n=100	0.230±0.007 σ=0.051 n=50	0.452±0.011 σ=0.081 n=50	0.337±0.013 σ=0.089 n=50
Fulcaster	0.161±0.008 σ=0.060 n=55	0.187±0.010 σ=0.050 n=25	0.469±0.020 σ=0.098 n=25	0.270±0.007 σ=0.065 n=100	0.232±0.010 σ=0.072 n=50	0.462±0.011 σ=0.078 n=50	0.340±0.010 σ=0.074 n=50
Poole	......	0.178±0.010 σ=0.051 n=25	0.409±0.025 σ=0.123 n=25	0.358±0.008 σ=0.083 n=100	0.244±0.008 σ=0.060 n=50	0.409±0.011 σ=0.080 n=50	0.314±0.012 σ=0.082 n=50
Harvest Queen	0.139±0.013 σ=0.069 n=30	0.193±0.010 σ=0.048 n=25	......	0.283±0.006 σ=0.062 n=100	0.181±0.008 σ=0.054 n=50	0.381±0.012 σ=0.085 n=50	0.291±0.009 σ=0.060 n=50
Purplestraw	......	0.180±0.015 σ=0.075 n=25	......	0.319±0.007 σ=0.069 n=100	0.207±0.008 σ=0.057 n=50	0.439±0.010 σ=0.072 n=50	0.295±0.018 σ=0.088 n=23

*All errors are standard errors.

Cold resistance is definitely associated with a number of plant characteristics and this phase of winterhardiness has received intensive study. Many workers have reported on physical and chemical phenomena associated with resistance to injury from low temperatures. Newton (7) has shown that accumulation of starch in the leaf and crown tissues is definitely associated with frost resistance. This starch, at temperatures slightly above freezing, changes to sugar, thus increasing the concentration of the cell sap and lowering its freezing point. It also prevents coagulation of the protoplasm. Accumulation of starch indicates a slowing up of active growth and the storage of the products of photosynthesis in reserve forms. Hence, cold-resistant lines would be expected to make smaller growth than the cold-susceptible, which utilize a greater proportion of the elaborated plant food in active growth.

This implies that cold resistance and vigorous growth cannot be combined. This may be true if the highest degree of cold resistance is to be attained, but reasonable resistance to low temperatures can probably be combined with vigorous growth. The present findings would indicate this characteristic to be necessary in a variety able to withstand heaving.

From a comparison of the S Series results with the others, it is evident that the cross sectional area of seedling roots does not correlate with the size of permanent roots on the same variety. Furthermore, there is much less difference between varieties. Hence, a study of seedling roots would appear of little value.

In the case of the H, 2W, and 2C Series, the plants had passed through the winter before the measurements of root diameter were made. During the dormant period, certain definite changes took place. The central vascular stele for the most part remained intact, but the epidermal and cortical regions either sloughed off in some degree or were actually torn away. In any case, the diameter of the roots as measured in the spring was less than that in the fall in every case.

In the case of the H and 2W Series, the determinations were made before there was any appreciable spring growth. At Ithaca in the spring of 1935, however, conditions were such that growth started some time before danger of damage from heaving was past, and the roots especially had made considerable growth before the 2C Series was run. Undoubtedly, this is reflected in the results and is particularly evident in the data on breaking tensions.

Histological examination of root specimens indicated clearly that the vascular stele is usually uninjured by the winter season and that the smaller diameter is due solely to disintegration, sloughing off, or tearing away of the epidermal and cortical tissues. The endodermis is nearly always intact and its cell walls are normally very definitely thickened, especially on the inner side. Walls of all cells inside the endodermis are thickened, but the walls of cortical and epidermal cells are not. This accounts for the ease with which the outer root covering sloughs off or is torn away, giving the large reduction in diameter with but little effect on the breaking strength of the root. This is clear from observation of the cortical tissue remaining in the spring. When a root is stretched, it commonly separates and leaves a section of vascular stele exposed long before the root breaks. Cortical tissue thus plays no part in either breaking tension or extensibility of the root. In all probability it has little influence on these root characters even in the fall, although at that time it very often remains intact during the breaking process. Figure 4 shows typical wheat roots at different seasons.

A—**Typical young permanent root, cortex intact, thickening beginning in vascular tissue**

B—**Typical permanent root in late fall, cortex intact, pronounced thickening in vascular tissue**

C—**Typical permanent root in spring, cortex severely damaged, vascular stele intact**

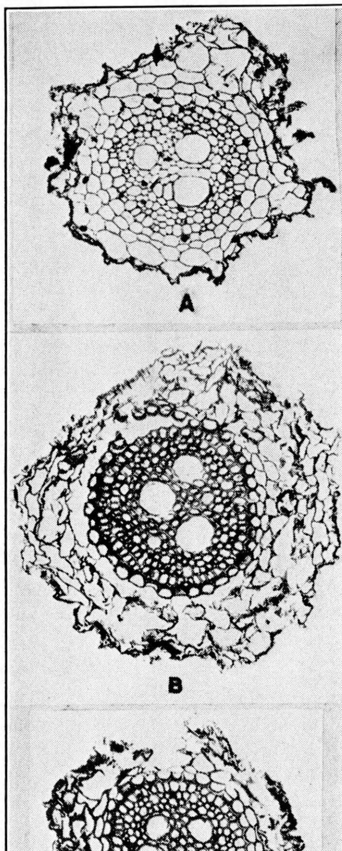

Fig. 4

The change in root diameter from fall to spring does not show any constant or consistent differences between varieties. The decrease is not even proportional to the original root size. This may be partly, but is certainly not solely, due to varietal differences in relative diameter of vascular tissue and cortex. Measurements of root size in the fall before there is serious injury or collapse of cortical tissue probably give some indication of the size of the vascular stele and are, therefore, of greater use in studying the relation of the size of root to other characteristics of the plant. Measurement of the diameter of the vascular stele, as well as the total diameter, is necessary before any but the most general conclusions can be drawn.

The capacity of the root to retain the cortical tissue through the spring may have a practical significance. When plants are heaved from the soil by alternate freezing and thawing, they are often killed by desiccation. The roots are dried out by sun and wind, the moisture supply of the plant is cut off, and it dies. If cortical tissue, even though dead, were still present on these exposed roots, it seems reasonable that it would reduce the rate of water loss in some measure and thus be a factor in the ultimate fate of the plant. Further work is necessary to determine whether this is true and also whether varieties differ in this regard. Since large roots have relatively less surface for their volume and a larger water conducting tissue as well, size of root in itself may be important.

The winter of 1934-1935 was not as severe at Wooster as was that of 1933-1934. Wheat had nearly as good a start in the fall of 1933 as it had a year later, and a comparison of the H and 2W Series gives a rough indication of the effect of season on the varieties. Evidently, root size was consistently less in the H Series and most of this difference must be ascribed to the more severe weather. The ground was frozen solid on several occasions in January and February, 1934, and, though no heaving occurred, apparently the stresses involved were sufficient to cause the loss of most of the cortical tissue from the roots. There was no indication that varieties differed in ability to retain cortical tissue, but the technique employed may not have brought this out clearly.

Low temperature directly is the most important cause of winter injury to wheats of the Great Plains area of the United States. In the northeastern section of the country, on the contrary, heaving is probably paramount. Heaving is important not so much because of less intense cold as because of higher precipitation in the winter and early spring and more frequent thaws. Since the characteristics of climate change progressively from west to east, it would seem reasonable to assume that there is no sudden transition from a region of typical cold injury to one of typical heaving damage.

A second assumption that would appear valid is that new varieties of wheat, developed at state experiment stations, would be well adapted to the immediately surrounding regions. On this basis, it is interesting to note how size of root varies with the location at which the variety was developed. Table 3 presents these data from the W and C Series. Kharkov is included with Minhardi as typical of the cold-resistant wheats of the Great Plains area.

TABLE 3.—Relation of Root Size to State of Origin

State of origin	Varieties	Mean cross sectional area in sq. mm.		
		W series	C series	Average
Minnesota	Minhardi (Kharkov)*	0.224	0.352	0.288
Indiana	Purkof, Purdue No. 1	0.251	0.406	0.328
Michigan	Red Rock	0.313	0.434	0.374
Ohio	Trumbull, Fulhio, Nabob, Gladden	0.344	0.439	0.391
Pennsylvania	Nittany	0.399	0.660	0.530
New York	Valprize	0.304	0.452	0.378

*Not a Minnesota introduction.

Root size, except in the case of the New York variety, shows progressive increase from west to east and the rank is the same in both series. The standard error of the difference can be roughly computed from the average error for a single variety, since the individual errors are of about the same magnitude. These are 0.007 mm.^{2} for the W and 0.011 mm.^{2} for the C Series. The error of the difference then can be taken as roughly $\sqrt{2(Es)^2}$, or 0.010 mm.^{2} for the W and 0.016 mm.^{2} for the C Series. In most cases, the differences in Table 3 are statistically significant, especially in the Wooster-grown test.

The behavior of Valprize gives grounds for belief that conditions in New York are probably of the same general type as those of the rest of the region considered, but this variety does not fit into the geographical sequence of the table. The generally colder climate, due not only to latitude but also to the fact that the isotherms of the northern United States and southern Canada run from southeast to northwest, accounts for this. Resistance to low temperature is important in spite of snow protection. If New York is ranked between Indiana and Michigan, it fits well into both series. The locations where only one variety is available for the table must be considered as subject to considerable error.

Root size of the winter wheats studied varies considerably. It shows a clear correlation with region of origin, and this in turn can be associated with climatic variations. These differences in climate are of fundamental importance in determining the type of winter injury most likely to damage the crop. Large roots and accompanying vigorous fall growth are typical of wheats from regions where heaving may occur; restricted fall growth is the rule with varieties which must withstand very low temperatures.

Finally, it should be noted that the growth which a variety will make in the fall is determined more by the response to unfavorable growing conditions than it is by an inherent limit to growth before the rest period begins. This is borne out by data given later in this paper and no doubt accounts for the change in rank of varieties in the W and C Series; also it explains why differences between varieties are less clear-cut in the Ithaca planting.

A study of the distribution of precipitation at the different stations is useful in determining the areas where heaving damage is most likely to occur. The usual time for such injury is early spring, before or just about the time that growth begins. Table 4 gives the average precipitation for certain months and for longer periods for the stations from which varieties tested have come.

Total annual precipitation varies from less than 30 inches to more than 40 inches. This is less important from the standpoint of danger of heaving than is the distribution of the rainfall. The rainfall for all stations from May to August, inclusive, does not vary greatly. This is of practically no importance to soil moisture conditions in early spring. Rain falling from September to December, inclusive, is more important since the evaporation rate is lower for these months. Precipitation for the first 4 months of the year is very important, as it influences the height of the ground water table and the degree of saturation of the surface and subsoils at the time when heaving occurs. March and April rainfall are particularly important in their relation to producing soil conditions such that heaving is possible, provided freezing and thawing occur.

At St. Paul, it is ordinarily too dry for serious heaving. At Lafayette, Wooster, and State College, conditions are such that heaving may readily occur. At East Lansing and Ithaca, there would seem to be somewhat less danger. It must be remembered, however, that precipitation is not the only factor governing the likelihood of the occurrence of heaving. Soil type is important and the normal height of the ground water table must be taken into consideration. The prevalence of weather conditions involving alternate freezing and thawing is

TABLE 4.—Data on Precipitation at Several Experiment Stations

Station	State	Number years averaged	January	February	March	January to March, inclusive	April	May to August, inclusive	September to December, inclusive	Annual
St. Paul	Minn.	49	0.90	0.84	1.60	3.34	2.57	14.90	8.12	28.93
Lafayette	Ind.	40	2.64	2.69	3.10	8.43	3.39	15.80	9.76	37.38
East Lansing	Mich.	56	2.09	2.02	2.26	6.37	2.64	13.83	9.34	32.18
Wooster	Ohio	39	3.31	2.71	3.60	9.62	2.60	15.73	11.33	39.28
State College	Pa.	35	2.95	2.91	3.40	9.26	3.24	16.74	10.88	40.12
Ithaca	N. Y.	41	2.16	1.87	2.44	6.47	2.29	13.45	11.22	33.43

very important. Nevertheless, the danger of heaving is probably greatest in those areas with high spring rainfall; this assumption agrees well with the data of Table 3.

STRETCHING CAPACITY OF ROOTS

The ability of roots of winter wheats to stretch is probably of prime importance in saving them from damage when the ground freezes. Even though the volume changes involved are comparatively small, the forces acting on the root are enormous, and, unless it has some ability to accommodate itself by stretching, it will undoubtedly be severely injured. Stretching capacity may be related to the ability of the plant to resist pulling out of the ground when heaving occurs. There is no evidence supporting this assumption, but varieties are certainly affected in varying degrees.

Elasticity, in addition to mere stretching, may have greater importance. No study of elasticity has been made, but, from handling several thousand roots, it would appear that the ability of the root to regain its original state, or even partially to do so, is proportional to the stresses to which it has been subjected. Thus, if taken in the fingers and pulled lightly, roots are elastic in some degree; whereas, if stretched almost to the breaking point, they recover but little or else very slowly. Further studies are required on this point.

Both machines in which the root tests were run permitted the determination of the amount of stretch at the breaking tension and the first one constructed also showed the course of the stretching as the tension increased. The data on stretch at breaking tension are presented in Table 5 in exactly the same form as the corresponding data for root size in Table 3. Except in the 2W Series, no significant number of roots slipped in the clamps. However, the cortical tissue of roots that had passed through the winter separated very readily from the vascular stele. Whether or not this vascular stele could slip inside the cortical tissue in the clamps could not be determined absolutely, but careful observation failed to show that this did occur. Probably, the average stretch as presented is a fairly good measure of the ability of roots to accommodate themselves to changes in soil volume.

The results of the 2W and 2C determinations interfere seriously with drawing clear-cut deductions from Table 5. In the case of the 2W Series, the difficulty probably lay in the clamp linings. These deteriorate and harden in strong light. The apparatus had been kept in a greenhouse from fall to spring, and the rubber facings were not replaced before the 2W Series was run. The result was that, with strong roots, slippage did occur. This is evident from the higher correlation of breaking tension with stretch for any one variety, from the wider discrepancies for the stronger rooted varieties, and from the progressive increase in error in the order in which the tests were run. For example, Fulhio was the second variety tested and Fulhio (pure line) was the last. In the W Series these gave almost identical results, as was expected, but in the 2W Series the pure line showed a large apparent increase in extensibility from fall to spring. Gladden and Nittany results are inaccurate because of the strong roots these varieties possess. The data, which almost certainly should show a decreased ability to stretch from the W to 2W Series, are inconclusive. The error was not apparent until the data were calculated from the graphs.

TABLE 5.—Mean Extensibility of Roots of Winter Wheat Varieties*

(Mm. stretch per Cm. section)

Variety	Series H	Series S	Series 2S	Series W	Series 2W	Series C	Series 2C
Minhardi	3.54±0.07 σ=0.80 n=125	4.56±0.16 σ=0.78 n=25	...	4.02±0.07 σ=0.65 n=100	4.49±0.11 σ=0.81 n=50	4.17±0.10 σ=0.69 n=50	4.53±0.07 σ=0.52 n=50
Kharkov	...	5.13±0.18 σ=0.90 n=25	...	4.32±0.08 σ=0.75 n=100	4.43±0.10 σ=0.72 n=50	4.32±0.11 σ=0.75 n=50	4.79±0.07 σ=0.48 n=50
Purkof	3.47±0.14 σ=0.76 n=30	4.79±0.18 σ=0.88 n=25	...	4.95±0.06 σ=0.63 n=100	5.19±0.12 σ=0.83 n=50	4.52±0.08 σ=0.62 n=50	5.18±0.09 σ=0.66 n=50
Purdue No. 1	...	4.96±0.14 σ=0.69 n=25	...	5.16±0.06 σ=0.64 n=100	4.84±0.13 σ=0.95 n=50	5.26±0.07 σ=0.51 n=50	5.39±0.09 σ=0.64 n=50
Red Rock	3.77±0.17 σ=0.84 n=25	5.60±0.16 σ=0.81 n=25	5.28±0.18 σ=0.90 n=25	5.18±0.08 σ=0.77 n=100	4.93±0.17 σ=1.22 n=50	5.39±0.12 σ=0.92 n=89	5.16±0.08 σ=0.57 n=50
Trumbull	...	5.28±0.13 σ=0.63 n=25	5.39±0.13 σ=0.63 n=25	5.60±0.07 σ=0.66 n=100	4.55±0.11 σ=0.76 n=50	5.09±0.09 σ=0.65 n=50	5.31±0.10 σ=0.71 n=50
Fulhio	3.91±0.08 σ=0.84 n=125	4.93±0.14 σ=0.69 n=25	4.65±0.10 σ=0.52 n=25	5.37±0.07 σ=0.65 n=100	4.86±0.15 σ=1.09 n=50	5.44±0.11 σ=0.77 n=50	5.19±0.12 σ=0.83 n=50
Fulhio (Pure Line)	...	...	...	5.40±0.07 σ=0.69 n=100	6.07±0.14 σ=0.96 n=50	...	...

*All errors are standard errors.

TABLE 5.—Mean Extensibility of Roots of Winter Wheat Varieties*—Continued

(Mm. stretch per Cm. section)

Variety	Series H	Series S	Series 2S	Series W	Series 2W	Series C	Series 2C
Nabob	...	5.02±0.13 σ=0.64 n=25	4.93±0.06 σ=0.78 n=25	5.08±0.07 σ=0.68 n=100	4.67±0.10 σ=0.71 n=50	5.21±0.08 σ=0.55 n=50	5.41±0.09 σ=0.66 n=50
Gladden	3.89±0.06 σ=0.62 n=125	4.47±0.11 σ=0.57 n=25	4.67±0.11 σ=0.57 n=25	5.28±0.06 σ=0.63 n=100	5.87±0.15 σ=1.09 n=50	5.09±0.09 σ=0.63 n=50	5.45±0.09 σ=0.60 n=50
Nittany	...	4.97±0.18 σ=0.89 n=25	...	5.29±0.08 σ=0.78 n=100	6.39±0.22 σ=1.56 n=50	5.38±0.14 σ=1.07 n=57	5.57±0.09 σ=0.62 n=50
Valprize	3.99±0.14 σ=0.70 n=25	4.67±0.15 σ=0.75 n=25	...	4.62±0.06 σ=0.62 n=100	4.87±0.14 σ=1.01 n=50	4.45±0.07 σ=0.47 n=50	4.84±0.09 σ=0.64 n=50
Fulcaster	3.77±0.13 σ=0.99 n=55	4.92±0.14 σ=0.68 n=25	4.67±0.12 σ=0.59 n=25	5.25±0.07 σ=0.66 n=100	5.19±0.13 σ=0.94 n=50	5.36±0.09 σ=0.66 n=50	4.95±0.12 σ=0.84 n=50
Poole	...	4.48±0.14 σ=0.72 n=25	4.63±0.20 σ=0.99 n=25	4.98±0.07 σ=0.73 n=100	5.11±0.12 σ=0.82 n=50	4.57±0.07 σ=0.50 n=50	5.21±0.10 σ=0.71 n=50
Harvest Queen	3.20±0.27 σ=1.47 n=30	5.04±0.15 σ=0.74 n=25	...	5.28±0.07 σ=0.72 n=100	5.20±0.17 σ=1.20 n=50	4.45±0.16 σ=1.12 n=50	5.65±0.08 σ=0.57 n=50
Purplestraw	...	4.60±0.13 σ=0.63 n=25	...	4.99±0.08 σ=0.82 n=100	4.86±0.13 σ=0.92 n=50	4.64±0.10 σ=0.88 n=50	5.43±0.17 σ=0.81 n=23

*All errors are standard errors.

With the C and 2C Series, in the great majority of cases, the varieties also showed greater stretching ability in the spring than in the fall. This, however, cannot be attributed to slippage but is probably due to the influence of renewed growth activity which had definitely started. This influence is even more clearly evident in the data on breaking tension. The difficulty arose because growth started some time before danger of damage from heaving was past.

The data from the H Series compared with the 2S, W, and C results indicate that the winter season may greatly reduce the extensibility of the roots. This agrees with the findings of Kokkonen with rye and is to be attributed to the non-elastic properties of the roots. Under the stresses of freezing and thawing the roots are stretched and do not recover completely. Thus, the extensibility is reduced when spring series are run. From the behavior of the 2C Series, it is evident that as growth starts again the roots regain their ability to stretch. From the point of view of the present study, however, this has little significance.

While the evidence is admittedly scant, it seems probable that the extensibility of the roots of winter wheat plants decreases as the winter proceeds and is proportional to the amount of stretching to which the roots have been subjected by soil freezing and thawing.

The ability of wheat roots to stretch without breaking varies from one variety to another. In general, the cold-resistant wheats show less extensibility. Varieties with strong roots have greater stretching ability than those with weaker roots, but differences are evident among varieties with approximately equally strong roots. Differences between varieties are not very large and, while the extensibility of roots is undoubtedly of fundamental importance in the ability of varieties to overwinter safely, there is no indication that any of those studied were deficient in this regard to the point where it became a determining factor in survival. With severe heaving damage, whether or not it might become a factor of importance only further study can show.

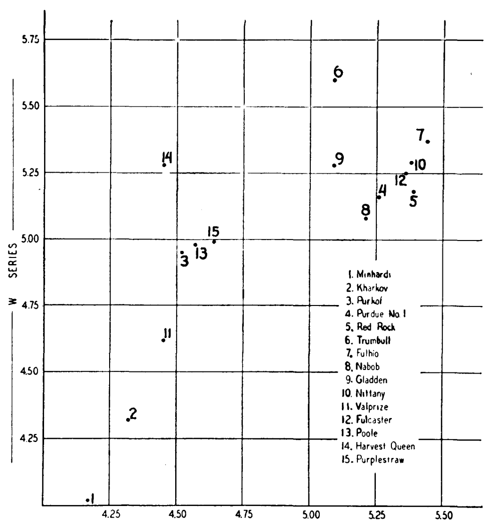

Fig. 5.—Correlation of extensibility of winter wheat roots of the W Series with those of the C Series

There is reasonably good agreement between the results of W and C Series insofar as extensibility of roots is concerned. Figure 5 presents the data graphically. Trumbull and Harvest Queen are distinctly out of line in the W Series, but otherwise there are no very marked deviations. The relation of the series to one another may not be a simple linear one when the more cold-resistant lines are included in the group studied. This indicates that, under the widely different growing conditions represented, the relative development in one series as compared to the other is not a constant for all varieties, a fact which is not surprising.

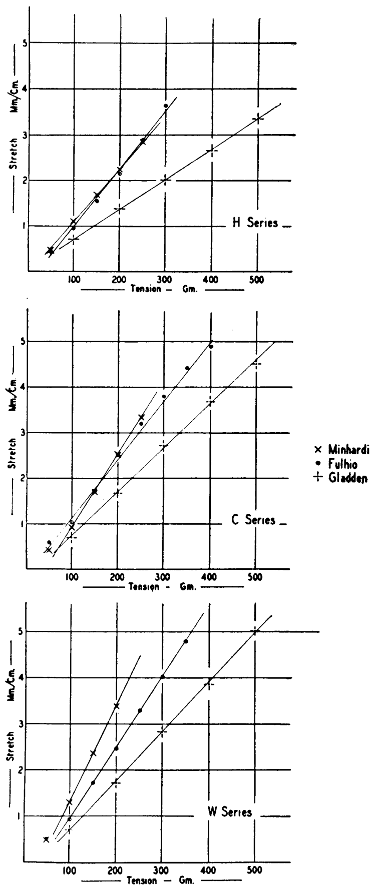

Fig. 6.—Graph showing linear character of the amount of stretch as a function of increasing tension.

A study of the graphs traced by the first apparatus indicated that the amount of stretch was in general a linear function of the tension. To test this, Minhardi, Fulhio, and Gladden were more carefully examined in several series. Graphs of a number of roots which had approximately the mean breaking tension and stretch for the variety were chosen and the stretch plotted against the tension. In every case the results were very close to a straight line. There was some indication, in many cases not evident from the figures given here, that just before a root breaks there was a somewhat more rapid stretching rate. This was probably due to the rupture of some of the supporting tissue, thus throwing an extra stress upon that remaining, which stretched more rapidly in consequence.

Table 6 presents the results of these calculations on Minhardi, Fulhio, and Gladden for the H, W, and C Series. The stretch was read for every 50 grams added tension for Minhardi and Fulhio because of their lower breaking tension and for every 100 grams added tension for Gladden. The calculated values assume a linear relation to exist from zero tension (and zero stretch) to the stretch for the maximum tension considered for the particular variety and series. The same data are shown in graphic form in Figure 6.

It must be kept in mind when interpreting the graphs that varieties differ not only in the amount of stretch but also in breaking tension. Thus, in the H Series, the fact that the lines for Minhardi and Fulhio almost coincide does not indicate that these varieties are the same in either breaking tension or stretch at breaking tension but only shows that the amount of stretch per unit of tension added is the same in both cases.

TABLE 6.—Relation Between Stretch of and Tension on Winter Wheat Roots

Calculated figures are linear

Series	Variety		Stretch in mm. per cm. of root section for tension in grams indicated at head of column									
			50	100	150	200	250	300	350	400	450	500
H	Minhardi (15)*	Actual	0.47	1.10	1.68	2.24	2.86	...	...	...	...	...
		Calculated	0.57	1.14	1.72	2.29	2.86	...	...	...	...	...
	Fulhio (11)	Actual	0.43	0.95	1.54	2.15	2.90	3.63	...	...	...	...
		Calculated	0.43	1.07	1.71	2.35	2.99	3.63	...	...	...	...
	Gladden (15)	Actual	...	0.70	...	1.39	...	2.02	...	2.67	...	3.36
		Calculated	...	0.67	...	1.34	...	2.02	...	2.69	...	3.36
C	Minhardi (9)	Actual	0.41	0.92	1.69	2.52	3.33	...	...	...	...	...
		Calculated	0.67	1.33	2.00	2.66	3.33	...	...	...	...	...
	Fulhio (8)	Actual	0.58	1.03	1.72	2.52	3.19	3.79	4.42	4.89	...	...
		Calculated	0.61	1.22	1.83	2.45	3.06	3.67	4.28	4.89	...	...
	Gladden (13)	Actual	...	0.69	...	1.67	...	2.71	...	3.68	...	4.51
		Calculated	...	0.90	...	1.80	...	2.71	...	3.61	...	4.51
W	Minhardi (17)	Actual	0.47	1.30	2.37	3.39	...	...	...	...	...	...
		Calculated	0.85	1.70	2.54	3.39	...	...	...	...	...	...
	Fulhio (9)	Actual	0.49	0.92	1.71	2.47	3.29	4.01	4.79	...	...	...
		Calculated	0.68	1.37	2.05	2.74	3.42	4.11	4.79	...	...	...
	Gladden (15)	Actual	...	0.69	...	1.71	...	2.83	...	3.86	...	5.01
		Calculated	...	1.00	...	2.00	...	3.01	...	4.01	...	5.01

*Numbers in parentheses indicate number of roots used in each case.

In the case of the W Series and to a lesser degree the C Series also, when a straight line is fitted to the graph, it seems evident that some small tension on the root is required before it begins to stretch at its normal rate. This increases the differences between the calculated and actual figures in Table 6. The reason for this behavior is not clear. It is characteristic for roots that have never been subjected to stretching, since it is not evident in the H Series results. The apparent differences between the W and C Series may indicate that the varieties change with growing conditions or state of maturity of the roots. It probably has no significance in the response of varieties to heaving.

BREAKING TENSION OF ROOTS

The tension necessary to break the roots shows great variation among the varieties included in this study. It constitutes a clear-cut basis upon which to group varieties and offers the greatest promise of any single characteristic studied as a basis for an empirical technique. Table 7 gives the mean breaking tension in grams for each of the 15 varieties in the various series. While minor deviations do occur, results are in general agreement, with the exception of those for the S Series. Seedling roots show much smaller differences between varieties and no agreement at all with the other series. This again emphasizes the fact that seedling roots are of little value in studying root characteristics. The small differences between varieties in the S Series are in line with the contention that the larger differences found between permanent roots are due more to arrested development of some varieties than to inherent differences in growth capacity.

There is a general association between root size of a variety and the breaking tension. The smaller rooted sorts have the lower breaking tension. However, varieties with similar sized roots, as, for example, Red Rock and Purplestraw or Purkof and Kharkov, may vary considerably in root strength. Whether this variation is due to differences in size of vascular stele, to differences in size of cells or in degree of thickening of the cell walls, or to variation in the chemical or physical nature of the thickened walls cannot be determined without rather extensive histological studies.

Figure 7 shows the means of the C Series plotted against those of the W Series. Correlation is high for the data as a whole, but for varieties lying between the extremes there is no clear-cut order indicated. This again is due to the great differences in the environment during the fall growing period, resulting in the cessation of growth at widely different stages of development. In spite of this, however, it is possible to separate varieties with very strong roots from those of medium strength with reasonable accuracy. If it is shown, therefore, that any association exists between strong roots and resistance to heaving, then it should be possible to eliminate from a breeding nursery a large number of new lines that eventually would have a high probability of being discarded on the basis of lack of winterhardiness.

If the only factor causing differences in breaking tension were size of root, then the breaking tension per unit of cross sectional area should be a constant. Grams tension at the breaking point per square millimeter of cross sectional area were calculated for each root, and the mean values for each variety and series are presented in Table 8. It is evident that real differences exist among varieties. Some of the variation is due to the fact that different proportions of the total cross section are vascular tissue, but this probably cannot account

TABLE 7.—Mean Breaking Tension of Roots of Winter Wheat Varieties (Grams)*

Variety	Series H	Series S	Series 2S	Series W	Series 2W	Series C	Series 2C
Minhardi	294.0± 9.1 σ=102.0 n=125	172.0± 9.4 σ=47.0 n=25		246.0± 10.2 σ=102.0 n=100	234.0± 13.9 σ= 98.0 n= 50	304.0± 14.8 σ=104.5 n= 50	395.0± 17.0 σ=120.0 n= 50
Kharkov		172.0± 9.4 σ=47.1 n=25		292.0± 11.7 σ=116.5 n=100	280.0± 14.7 σ=104.0 n= 50	334.0± 14.9 σ=105.0 n= 50	408.0± 19.9 σ=141.0 n= 50
Purkof	368.3±17.3 σ=94.5 n=30	194.0± 7.1 σ=35.6 n=25		361.5± 7.4 σ= 74.0 n=100	345.0± 13.9 σ= 98.0 n= 50	415.0± 13.7 σ= 92.0 n= 50	554.0± 21.4 σ=151.0 n= 50
Purdue No. 1		184.0± 9.7 σ=48.4 n=25		414.0± 6.9 σ= 69.0 n=100	326.0± 15.3 σ=108.0 n= 50	519.0± 14.1 σ= 99.5 n= 50	562.0± 18.1 σ=128.0 n= 50
Red Rock	414.0± 24.7 σ=123.7 n= 25	242.0±11.6 σ=58.0 n=25	378.0± 25.8 σ=129.0 n= 25	473.5± 9.2 σ= 92.0 n=100	379.0± 19.5 σ=138.0 n= 50	452.8± 18.4 σ= 45.5 n= 89	637.0± 19.4 σ=138.0 n= 50
Trumbull		198.0±10.5 σ=52.5 n=25	536.0± 22.9 σ=114.5 n= 25	374.0± 8.9 σ= 88.5 n=100	375.0± 14.7 σ=104.0 n= 50	443.0± 16.1 σ=114.0 n= 50	608.0± 19.4 σ=137.0 n= 50
Fulhio	353.2± 9.0 σ=101.0 n=125	178.0± 9.8 σ=49.2 n=25	418.0± 21.9 σ=109.5 n= 25	385.5± 11.6 σ=116.0 n=100	396.0± 16.4 σ=116.0 n= 50	479.0± 16.2 σ=114.5 n= 50	552.0± 28.7 σ=203.0 n= 50
Fulhio (Pure Line)				372.0± 9.7 σ= 97.0 n=100	430.0± 16.7 σ=118.0 n= 50		

*All errors are standard errors.

TABLE 7.—Mean Breaking Tension of Roots of Winter Wheat Varieties (Grams)*—Continued

Variety	Series H	Series S	Series 2S	Series W	Series 2W	Series C	Series 2C
Nabob	....	200.0± 9.8 σ= 49.0 n= 25	350.0± 22.3 σ=111.5 n= 25	383.0± 8.4 σ= 84.0 n=100	456.0± 19.1 σ=135.0 n= 50	418.0± 10.7 σ= 76.0 n= 50	459.0± 22.3 σ=158.0 n= 50
Gladden	542.4± 11.7 σ=131.0 n=125	192.0± 8.8 σ= 44.0 n= 25	454.0± 24.6 σ=123 n= 25	534.0± 9.8 σ= 98 n=100	493.0± 20.2 σ=143.0 n= 50	547.0± 15.7 σ=111 n= 50	687.0± 22.5 σ=159.0 n= 50
Nittany	....	190.0± 8.0 σ= 40.0 n= 25	....	556.0± 11.6 σ=116.5 n=100	477.0± 18.2 σ=129.0 n= 50	936.0± 39.0 σ=296 n= 57	718.0± 27.4 σ=194.0 n= 50
Valprize	390.0± 21.6 σ=107.7 n= 25	184.0± 10.1 σ= 50.5 n= 25	....	445.0± 10.0 σ=100.0 n=100	391.0± 15.7 σ=111.0 n= 50	452.0± 15.7 σ=111.0 n= 50	534.0± 16.9 σ=120.0 n= 50
Fulcaster	510.9± 25.5 σ=189.5 n= 55	188.0± 9.1 σ= 45.4 n= 25	474.0± 23.5 σ=117.5 n= 25	381.0± 9.1 σ= 91.0 n=100	360.0± 15.7 σ=111.0 n= 50	493.0± 15.4 σ=109.0 n= 50	630.0± 23.9 σ=169.0 n= 50
Poole	....	192.0± 10.4 σ= 52.0 n= 25	278.0± 18.6 σ= 93.0 n= 25	496.0± 11.9 σ=119.0 n=100	372.0± 16.1 σ=114.0 n= 50	463.0± 18.3 σ=129.5 n= 50	574.0± 24.2 σ=171.0 n= 50
Harvest Queen	283.3± 24.1 σ=132.0 n= 30	198.0± 8.2 σ= 41.2 n= 25	....	393.5± 10.6 σ=105.5 n=100	345.0± 17.4 σ=123.0 n= 50	451.0± 19.8 σ=140.0 n= 50	635.0± 19.0 σ=134.0 n= 50
Purplestraw	....	184.0± 9.3 σ= 46.3 n= 25	....	431.0± 11.3 σ=113.0 n=100	367.0± 15.3 σ=108.0 n= 50	382.0± 14.1 σ= 99.5 n= 50	494.0± 41.9 σ=201.0 n= 23

*All errors are standard errors.

for all of it. When fall and spring figures for the same planting are considered, particularly the W and 2W Series where no appreciable spring growth had taken place, the breaking tension in gm./mm.² is higher in the spring than in the fall. This is, of course, to be expected, since the actual breaking tension in grams is but little less after the winter while the reduction in size is considerable.

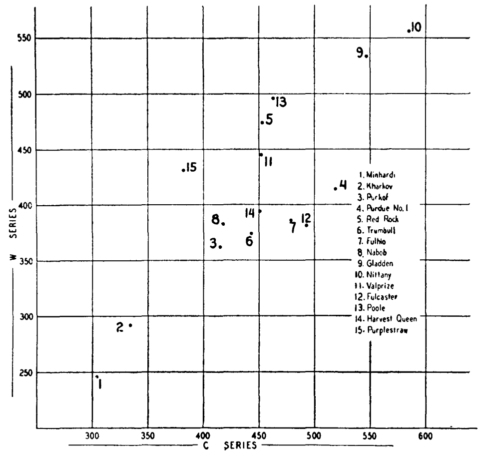

Fig. 7.—Correlation of breaking tension of winter wheat roots of the W Series with those of the C Series

The loss of diameter was much less in 1934-1935 than in 1933-1934. The strength in gm./mm.² was very high in the H Series for this reason. This emphasizes again that outside diameter is not the best measure of root size. To supplement this figure, the diameter of the vascular stele is needed. With both these measurements available, it would be possible to calculate accurately the proportion between vascular tissue and cortex, the proportion of cortex lost during the winter, and the loss of strength of the vascular tissue per square millimeter of its cross section. The necessary measurements can be readily made by using a high light intensity, as the shadow of the vascular stele is then quite definite. Work along this line is planned.

Minhardi in the Wooster planting shows a very large increase in strength (gm./mm.²) from the W to the 2W Series. This simply indicates a large percentage change in diameter from fall to spring. While the cross sectional area was smaller to begin with, the reduction overwinter was about the same as for several other varieties with considerably larger roots. In Table 8, data from the 2S, W, and C Series are much the best indices, since the cortex of the roots was nearly always intact.

The data in Table 8 must be accepted with distinct reservations, as is evident from the preceding discussion. At best, they can only indicate in a general way the type of varietal differences that really exist. Vascular tissue alone should be considered when studying strength of root, while for all practical purposes the epidermis and cortex only are involved in diameter changes of relatively mature roots.

TABLE 8.—Mean Breaking Tension of Roots of Winter Wheat Varieties*

(Gm. per $Mm.^2$ of root cross section)

Variety	Series H	Series S	Series 2S	Series W	Series 2W	Series C	Series 2C
Minhardi	2957 ± 103 σ = 1150 n = 125	1096 ± 79 σ = 396 n = 25		1240 ± 48 σ = 480 n = 100	2200 ± 139 σ = 980 n = 50	988 ± 45 σ = 316 n = 50	1556 ± 71 σ = 504 n = 50
Kharkov		2240 ± 220 σ = 1100 n = 25		1210 ± 42 σ = 424 n = 100	1740 ± 78 σ = 554 n = 50	900 ± 39 σ = 278 n = 50	1456 ± 77 σ = 542 n = 50
Purkof	3273 ± 199 σ = 1090 n = 30	1272 ± 77 σ = 384 n = 25		1502 ± 35 σ = 350 n = 100	2120 ± 81 σ = 576 n = 50	1136 ± 37 σ = 260 n = 50	1856 ± 74 σ = 520 n = 50
Purdue No. 1		1664 ± 145 σ = 726 n = 25		1698 ± 39 σ = 394 n = 100	1844 ± 91 σ = 644 n = 50	1204 ± 40 σ = 286 n = 50	1956 ± 66 σ = 464 n = 50
Red Rock	2280 ± 135 σ = 676 n = 25	1520 ± 111 σ = 554 n = 25	880 ± 72 σ = 358 n = 25	1560 ± 34 σ = 338 n = 100	1544 ± 74 σ = 526 n = 50	1062 ± 41 σ = 324 n = 89	1980 ± 57 σ = 404 n = 50
Trumbull		1168 ± 86 σ = 430 n = 25	1192 ± 78 σ = 392 n = 25	1152 ± 35 σ = 346 n = 100	1600 ± 73 σ = 516 n = 50	1060 ± 42 σ = 294 n = 50	1900 ± 71 σ = 504 n = 50
Fulhio	2362 ± 83 σ = 926 n = 125	1136 ± 90 σ = 448 n = 25	976 ± 73 σ = 366 n = 25	1216 ± 34 σ = 342 n = 100	1508 ± 77 σ = 544 n = 50	1244 ± 35 σ = 248 n = 50	1696 ± 77 σ = 542 n = 50
Fulhio (Pure Line)				1306 ± 36 σ = 356 n = 100	1856 ± 71 σ = 502 n = 50		

*All errors are standard errors.

TABLE 8.—Mean Breaking Tension of Roots of Winter Wheat Varieties*—Continued

(Gm. per Mm.[2] of root cross section)

Variety	Series H	Series	Series 2S	Series W	Series 2W	Series C	Series 2C
Nabob	....	1048± 88 σ= 440 n= 25	760± 56 σ= 278 n= 25	1168± 32 σ= 318 n= 100	1832± 85 σ= 598 n= 50	1048± 30 σ= 214 n= 50	1644± 70 σ= 494 n= 50
Gladden	2894± 91 σ=1012 n= 125	1232± 94 σ= 472 n= 25	880± 52 σ= 260 n= 25	1464± 35 σ= 346 n= 100	1632± 68 σ= 484 n= 50	1140± 36 σ= 254 n= 50	1856± 52 σ= 368 n= 50
Nittany	....	1456± 96 σ= 482 n= 25	....	1438± 32 σ= 324 n= 100	1448± 66 σ= 466 n= 50	936± 39 σ= 296 n= 57	1640± 64 σ= 450 n= 50
Valprize	2360± 147 σ= 735 n= 25	1160± 97 σ= 486 n= 25	....	1500± 36 σ= 362 n= 100	1736± 74 σ= 552 n= 50	1024± 35 σ= 246 n= 50	1660± 62 σ= 436 n= 50
Fulcaster	3364± 222 σ=1646 n= 55	1088± 89 σ= 446 n= 25	1064± 57 σ= 286 n= 25	1480± 47 σ= 468 n= 100	1648± 89 σ= 628 n= 50	1076± 34 σ= 240 n= 50	1864± 75 σ= 528 n= 50
Poole	....	1184± 103 σ= 516 n= 25	768± 78 σ= 390 n= 25	1436± 38 σ= 376 n= 100	1588± 70 σ= 494 n= 50	1152± 41 σ= 290 n= 50	1880± 72 σ= 510 n= 50
Harvest Queen	2693± 363 σ=1990 n= 30	1096± 67 σ= 334 n= 25	....	1446± 51 σ= 508 n= 100	1924± 99 σ= 698 n= 50	1204± 49 σ= 344 n= 50	2200± 62 σ= 436 n= 50
Purplestraw	....	1256± 131 σ= 656 n= 25	....	1366± 36 σ= 360 n= 100	1868± 95 σ= 674 n= 50	904± 41 σ= 292 n= 50	1704± 147 σ= 704 n= 23

*All errors are standard errors.

To return to the simple breaking strength of roots, it is interesting to compare the varieties according to station of origin, as was done in the case of root size. Table 9 presents these data in exactly the same form as Table 3.

Differences are not nearly so marked as in the case of root size, but the same general tendency is clearly evident. The New York variety may again be ranked between Indiana and Michigan without significant error. There is more change in rank evident between the C and W Series, in part due to the relatively higher standard errors and in part to less difference between means in the intermediate cases.

TABLE 9.—Relation of Root Strength of Winter Wheat Varieties to State of Origin

State of origin	Varieties	Mean breaking tension in grams		
		W series	C series	Average
Minnesota.....	Minhardi, (Kharkov)*	269	319	294
Indiana	Purkof, Purdue No. 1............................	388	467	428
Michigan......	Red Rock	474	453	464
Ohio...........	Trumbull, Fulhio, Nabob, Gladden............	419	472	446
Pennsylvania .	Nittany..	556	936	746
New York.....	Valprize	445	452	449

*Not a Minnesota introduction.

In the C Series, the average coefficient of variability for root size was 18.8 per cent; for breaking tension, 25.0 per cent. The corresponding coefficients for the W Series were 22.2 per cent and 25.1 per cent, respectively. Computing the standard error of difference, as was done for Table 3, gives 13.6 grams for the W and 24.3 grams for the C Series. The mean breaking tension for Nittany in the C Series is obviously abnormal, a fact borne out by its very large error.

On the theory that development stops at different stages for different varieties, greater discrepancies are to be expected in breaking tension than in size of root. When permanent roots start, they grow very rapidly and are characterized by large diameter except very near the growing tip. Changes that take place later are concerned with lignification of the vascular tissue and endodermis. The extent to which this thickening proceeds is determined by the length of time the plant continues to grow, and during this time little or no change in diameter takes place, except possibly a reduction due to collapse of cortical tissue. Thus, we may consider that we have a "mature" diameter for all varieties but that the breaking tension varies with the stage to which the thickening of the cell walls has proceeded.

CORRELATION STUDIES

To investigate the interrelationships of the root characteristics studied, three varieties of widely differing type were chosen; namely, Gladden, Fulhio, and Minhardi. Coefficients of correlation were calculated from the data of the W, C, 2W, and 2C Series. Because of the errors introduced in cross sectional area of root by the loss of cortical tissue over winter, coefficients involving breaking tension in grams per square millimeter were not calculated in the 2W and 2C Series. Those involving cross sectional area, however, were included. The data are presented in Table 10.

TABLE 10.—Coefficients of Correlation Between Root Characteristics of Three Winter Wheats*

Root characteristic	Variety	Series	n	Root characteristic: Cross section of root (Sq. mm.)	Stretch (Mm./cm.)	Breaking tension (Gm.)
Stretch (mm. per cm.)	Minhardi	W	100	+0.176±0.097		
		C	50	+0.068±0.141		
		2W	50	+0.103±0.140		
		2C	50	+0.206±0.135		
	Fulhio	W	100	+0.104±0.099		
		C	50	+0.075±0.141		
		2W	50	−0.004±0.141		
		2C	50	+0.180±0.141		
	Gladden	W	100	+0.002±0.100		
		C	50	+0.111±0.126		
		2W	50	−0.040±0.144		
		2C	50	+0.332±0.126		
Breaking tension (gm.)	Minhardi	W	100	+0.567±0.068	+0.562±0.068	
		C	50	+0.427±0.116	+0.434±0.115	
		2W	50	+0.654±0.081	+0.476±0.109	
		2C	50	+0.353±0.124	+0.454±0.112	
	Fulhio	W	100	+0.372±0.086	+0.696±0.052	
		C	50	+0.395±0.119	+0.706±0.071	
		2W	50	−0.015±0.141	+0.754±0.061	
		2C	50	+0.362±0.123	+0.407±0.118	
	Gladden	W	100	+0.342±0.088	+0.369±0.086	
		C	50	+0.174±0.137	+0.609±0.136	
		2W	50	+0.445±0.113	+0.629±0.085	
		2C	50	+0.552±0.098	+0.623±0.087	
Breaking tension (gm. per mm.^{2})	Minhardi	W	100	−0.118±0.099	+0.575±0.066	+0.610±0.063
		C	50	−0.146±0.137	+0.419±0.117	+0.783±0.055
	Fulhio	W	100	−0.378±0.086	+0.605±0.063	+0.677±0.054
		C	50	−0.345±0.124	+0.723±0.068	+0.797±0.052
	Gladden	W	100	−0.594±0.065	+0.297±0.091	+0.496±0.075
		C	50	−0.347±0.124	+0.518±0.103	+0.824±0.045

*All errors are standard errors.

Size of root and extensibility are not strongly correlated. All but two of the 12 coefficients are positive, indicating a slight tendency for extensibility to increase with size. The one case, Gladden in the 2C Series, where the r value is more than twice its error is probably a chance occurrence, although the values in the 2C Series are consistently the highest obtained. Growth conditions and variety apparently have no great effect on the size or significance of the coefficients.

Size of root is significantly correlated with breaking tension. All but two of the coefficients are more than twice their errors. Fulhio in the 2W Series is very abnormal in its behavior, but otherwise the results are consistent. The size of the coefficients is not large, indicating relatively little interdependence. This is surprising as it would naturally be expected that the correlation would be good. Probably the relationship would be closer between breaking tension and cross sectional area of the vascular stele, since the cortical and epidermal tissues contribute practically nothing to tensile strength and do not form a constant percentage of the total cross section.

The negative coefficients obtained between root size and the breaking tension per square millimeter of cross section are interesting. They indicate, in the Fulhio and Gladden varieties at least, a significant decrease in strength per unit of cross section as size increases. If this relationship should prove to be not truly linear, which is not at all unlikely in a relationship so involved, it might be a factor contributing to the low r values between root size and strength. If this were so, large coefficients in one correlation should be associated with small coefficients in the other. This is indeed the case, since Minhardi gives the largest r values for size and strength and the smallest for size and strength per unit of cross section.

Between stretch and breaking tension there is a moderately good positive correlation. This was expected in view of the linear relationship between these factors which has already been discussed. It indicates that strong roots stretch more than weak ones before breaking, a fact quite evident from the original data.

Stretch and breaking tension per square millimeter of cross section are significantly correlated. The coefficients are approximately the same in size as those between stretch and absolute breaking tension, indicating that root size is not a serious disturbing element in this relationship. No differences between varieties are evident.

Breaking tension and breaking tension per square millimeter of cross section show a good correlation. Thus, strong roots are stronger per unit of cross section than are weak roots, despite the fact that large roots are weaker per unit of cross section than are small.

There are two facts which must be kept in mind when considering these correlation coefficients. First, it must be remembered that breaking tension per unit of cross section is not an independent variable but is the quotient of absolute breaking tension by cross sectional area. Also, it must again be emphasized that the diameter as measured includes cortex as well as vascular stele and that extensibility and strength are practically entirely dependent on the vascular stele. Giving these considerations due attention, it appears that there is no very close correlation between any two of the three independent characteristics treated and, therefore, that measurements of all three are necessary to estimate their importance in the problem.

INCIDENTAL AND SUPPLEMENTARY EXPERIMENTS

It has been assumed that differences among winter wheat varieties in their ability to resist heaving must be largely due to differences in root systems. The major investigations have been carried out on the strength and extensibility of roots of a representative group of varieties, mainly because Kokkonen's work indicated that these characteristics were associated with winter behavior. However, it was recognized that other factors may well play important roles, and, as time and opportunity presented, several other possibilities were investigated. Some results are given in this section, although, for the most part, they must be considered inconclusive. They indicate, however, that other factors of possible importance exist and do vary markedly with variety.

NUMBER OF ROOTS PER PLANT

When the first series of root determinations was being run in the spring of 1934, it was noted that there seemed to be differences in number of roots per plant for different varieties. On 50 plants each of Fulhio and Gladden and on

28 plants of Minhardi, root counts were made. Since it was not possible to distinguish the seedling from the permanent roots readily at this season, no attempt was made to classify them.

At Cornell University, in the spring of 1935, a pot series was sown in the greenhouse to Minhardi, Fulhio, and Gladden. The number of leaves, tillers, and roots was recorded from plants studied at short intervals. In this case, a fairly accurate segregation of seedling from permanent roots could be made. The experiment was not carried past the point where the first permanent roots had reached the stage when they were fully as strong as dormant roots of the same varieties from the field.

Table 11 presents the data available from both these sources on number of roots per plant. Under field conditions, Fulhio and Gladden developed approximately the same number of roots, with indications that Fulhio may have had a significantly greater number. Minhardi had definitely fewer roots under identical conditions. In the Cornell Pot Series, when the plants were 49 days old, exactly the same relationship held, although in all cases there were more roots. Probably the number of roots developed in the fall varies with variety, and the number produced by any one variety, in turn, depends on the growing conditions.

TABLE 11.—Number of Roots per Plant for Three Varieties of Winter Wheat

Source of plants	Minhardi			Fulhio			Gladden		
	Seedling	Permanent	Total	Seedling	Permanent	Total	Seedling	Permanent	Total
H series counts	....	....	6.39	....	....	9.30	....	....	8.40
Cornell pot series:									
9 days old	3.0	....	3.0	4.0	....	4.0	3.3	....	3.3
11 days old	3.0	....	3.0	5.0	....	5.0	5.0	....	5.0
13 days old	3.0	....	3.0	5.0	....	5.0	4.7	....	4.7
15 days old	3.0	....	3.0	5.0	....	5.0	4.7	....	4.7
17 days old	3.0	....	3.0	5.0	....	5.0	5.0	....	5.0
19 days old*	3.0	....	3.0	5.0	....	5.0	4.7	....	4.7
22 days old†	3.0	....	3.0	4.3	....	4.3	5.3	0.7	6.0
25 days old	3.3	....	3.3	5.0	2.0	7.0	5.0	2.0	7.0
28 days old	3.5	4.5	8.0	5.0	4.0	9.0	5.0	3.0	8.0
31 days old	4.0	4.0	8.0	5.0	4.5	9.5	5.0	4.0	9.0
36 days old	4.0	4.0	8.0	5.0	5.5	10.5	5.0	7.0	12.0
49 days old	....	....	10.5	....	....	13.0	....	....	12.5

*Permanent roots first starting on Fulhio and Gladden.
†Permanent roots starting on Minhardi.

The number of roots on a plant may very well be related to its ability to withstand heaving, other things being equal. Granted a uniform average strength of root, the force necessary to raise the crown will vary directly with the number of roots. More important than this, however, is the fact that the greater the number of roots, the greater the root injury that the plant can suffer and still survive. A plant may die if dependent on one injured root for moisture supply; whereas it may survive if two or more roots are functioning in some degree. With severe heaving injury, many roots may be broken. It seems logical to suppose that the more roots a plant possesses, the greater its chances to survive such mutilation.

Table 11 also shows the number of roots per plant from early stages up to the time the first permanent roots are well developed. The number of seedling roots developed is characteristic of the variety as has been shown by other workers (13, 14). In this case, at least, it is proportional to the number of permanent roots that the variety produces. All the seedling roots are produced early in the life of the plant. The larger number in the cases of Fulhio and Gladden is due to one or two additional roots developing after the last have appeared on Minhardi. The data are subject to large error, since only three, and in one or two cases only two, plants of each variety were studied at each date. As a whole, they probably give a true picture since the time intervals are so short. In all cases, some difficulty in separating seedling from permanent roots arose, since the seeds were planted shallow and both types of roots had their origin at the same point on the stem.

ROOT STUDIES AT VARYING DISTANCES FROM THE STEM

If roots are strong near the stem but lose strength very rapidly as the distance from the stem increases, the strong section would be of little value to the plant. Five normal plants of average development were chosen from each of the varieties Minhardi, Fulhio, and Gladden in the spring of 1934 and all the well-developed roots on each plant tested by the usual procedure, except that determinations were run not only at 1-2.27 centimeters but also at 3-4.27 centimeters and 5-6.27 centimeters from the stem end. Results were sufficiently consistent that the mean values obtained are highly significant. The data are presented in Table 12.

TABLE 12.—Root Characteristics for Three Varieties of Winter Wheat Data for Three Distances from Stem End of Root

Characteristics studied	Distance from stem end	Minhardi (26 roots)	Fulhio (30 roots)	Gladden (30 roots)
	Cm.			
Cross sectional area of root, mm.²	1-2.27	0.097	0.118	0.128
	3-4.27	0.083	0.122	0.104
	5-6.27	0.075	0.102	0.075
Stretch at breaking tension, mm./cm.	1-2.27	3.56	4.34	4.23
	3-4.27	3.11	3.45	3.58
	5-6.27	3.05	2.84	3.16
Breaking tension, gm.	1-2.27	236	351	431
	3-4.27	175	236	296
	5-6.27	132	159	212
Breaking tension, gm./mm.²	1-2.27	2798	3521	3793
	3-4.27	2312	2235	3354
	5-6.27	2007	1865	2643

For all varieties there is a marked decrease in the size, stretching ability, and strength of root as the distance from the stem increases. The breaking tension decreases relatively more rapidly than does the size of root as is evident from the decreasing values of the breaking tension in gm./mm.². Roots are only about 50 per cent as strong at 5-6.27 centimeters from the stem as at 1-2.27 centimeters, but apparently the decrease becomes less rapid as the distance from the stem increases. Even at 5-6.27 centimeters from the stem, Gladden roots are but little weaker than Minhardi roots in the first section stretched.

Apparently, varietal differences remain constant, regardless of the section of root arbitrarily chosen for testing. The true significance of these figures cannot be estimated from the available data. Roots of all varieties branch more or less, and at 5-6.27 centimeters the true strength is that of the main root and its branches. Further work is necessary to determine where roots break when plants are pulled from the ground, and this would have to be carefully checked against the point of breakage when plants are heaved up by frost before the data could be safely applied to the problem at hand.

Branching of roots varies both with variety and with growing conditions. It might have significance in the survival of plants after heaving, if it happens that the main root and some of its branches are broken while other branches remain intact. Branch roots, lying in a more horizontal position, would be less subject to stretching and breaking than the main root and might survive better. This also indicates a possible significance to whether roots go straight down or penetrate the soil at an appreciable angle to the vertical. Worzella (15) has shown that varieties differ in this regard and found some association with winter survival. His results would indicate low temperatures directly as a major cause of winterkilling in the light of the present study.

INFLUENCE OF FERTILITY LEVEL

In 1928, an experiment was started at the Ohio Agricultural Experiment Station to study the response of varieties of corn, oats, and winter wheat to differences in fertility level. A 3-year rotation of these crops was set up on three blocks of Canfield silt loam soil of low natural fertility. Four fertility levels, designated A, B, C, and D, were established by adding 0, 1, 2, and 4 increments of fertilizers to adjacent strips in each block. Both stable manure and chemical fertilizers were used. Details of the applications are unimportant to this study but are fully discussed in a report on this experiment (5); suffice it to say that at the lowest level of fertility, represented by the natural soil without treatment, crops made restricted growth and yields were low. At the C level, growth and yields were about normal for good soils; and, on the D level, there was abundant vegetative growth and usually some increase in grain yields.

The varieties sown in this experiment for 1934-1935 included Minhardi and Fulhio. Samples of these varieties were taken at each fertility level and one root from each of 25 plants tested. The data from these tests are presented in Table 13.

Size of root increases with the fertility of the soil. This is natural since the top growth showed very clear differences from level to level. The amount of stretch is unaffected by the fertility level, and the difference between the varieties is roughly proportional to the corresponding differences in the W Series. However, it is, for some reason not ascertained, distinctly higher for both varieties than in the W Series. Breaking tension is surprising in that at the B level it is decidedly less than at the A level. At the C and D levels, however, it rises again much as might be expected. This behavior is reflected in the breaking tension in gm./mm.^{2}, since the progressive changes of root size and root strength with increasing fertility are not similar.

This series was purely incidental. Results cannot be considered as particularly reliable, since only 25 roots were run in each case. The point is certainly raised, however, that fertility level may have a very real effect on root characteristics. Varying the proportions of nutrients available to young plants has a marked effect on relative development of roots and tops and the type of root system. Adding fertilizers would certainly change these proportions, particularly if the soil were notably deficient in some element. Available phosphorus is low in the Canfield soil. Nitrogen could not have varied greatly, since only 4 pounds per acre were applied to the B level in the fall. The effect of the ratios among the elements N, P, and K must be investigated, as well as the effect of deficiencies of these elements, before any definite conclusions can be drawn.

TABLE 13.—Effect of Fertility Level on Root Characteristics of Winter Wheats

Variety	Root characteristic	Increments of fertility added			
		0 Level A	1 Level B	2 Level C	4 Level D
Minhardi	Cross sectional area, mm.^{2}	0.090±0.007	0.122±0.007	0.184±0.019	0.237±0.009
	Stretch at breaking tension, mm./cm.	4.93± 0.37	4.79±0.27	4.69±0.18	4.68±0.19
	Breaking tension, gm.	168±15.5	142±12.0	182±12.9	294±17.5
	Breaking tension, gm./mm.^{2}	2104±264	1392±154	1208±135	1240±64
Fulhio	Cross sectional area, mm.^{2}	0.201±0.014	0.331±0.017	0.354±0.015	0.403±0.018
	Stretch at breaking tension, mm./cm.	5.71±0.20	4.69±0.17	5.86±0.27	5.60±0.16
	Breaking tension, gm.	290±17.2	238±20.6	338±21.6	504±22.3
	Breaking tension, gm./mm.^{2}	1696±173	760±61	1016±61	1264±55

POT EXPERIMENTS

This series was referred to in the discussion on number of roots per plant. Its main interest lies in the light it throws on the assumption that some varieties cease growth in the fall earlier than others because they are more sensitive to adverse conditions, especially lower temperatures and unfavorable moisture relations. Under greenhouse conditions, these limiting factors are largely eliminated. The data from the Pot Series are presented in Table 14. Minhardi, Fulhio, and Gladden were the varieties included.

The data are compiled from few determinations. The figures given are the average of six or less tests in each case. This accounts for the occasional wide deviations from the expected.

In the region 1-2 centimeters from the stem end of the root, which was the section studied, it is evident that seedling roots mature early. The differences between seedling roots of varieties are again small, as in the S Series. Since the series includes tests over a time interval fully equivalent to the fall growth period, comparisons are justified.

As stated earlier, diameter reaches a maximum while the root is young. There is some increase for a period of approximately 2 to 3 weeks and then a gradual decrease as the epidermal and cortical tissues collapse. This is clearly indicated for the seedling roots and is probably equally true for the permanent, although the data are insufficient to prove it.

Very young roots have a restricted stretching capacity but soon develop a fairly high extensibility. As maturity approaches, the stretching ability increases slowly, probably to a maximum. At all stages the amount of stretch is roughly proportional to the maximum for each variety; that is, the rank of varieties remains roughly the same.

TABLE 14.—Root Characteristics of Winter Wheats Grown in Cool Greenhouse

Cornell Pot Series

Variety	Type of root	Age	Root cross section	Stretch	Breaking tension	
		Days	*Mm.*2	*Mm./cm.*	*Gm.*	*Gm./mm.*2
Minhardi	Seedling	9	0.207	4.56	96	467
		11	0.228	4.94	115	508
		13	0.217	5.06	113	523
		15	0.222	4.67	102	458
		17	0.203	3.94	88	442
		19	0.187	4.50	112	598
		22	0.168	5.50	148	895
		25	0.167	4.78	139	851
		28	0.198	5.58	169	858
		31	0.145	5.17	187	1290
		36	0.110	5.33	210	1864
	Permanent	25	0.220	4.33	100	427
		28	0.200	4.83	107	540
		31	0.243	5.25	213	880
		36	0.255	5.50	257	1152
		49	0.308	6.22	537	1773
Fulhio	Seedling	9	0.242	3.44	92	382
		11	0.260	4.56	106	406
		13	0.273	4.89	122	444
		15	0.250	4.94	106	423
		17	0.232	4.17	102	450
		19	0.232	4.83	108	489
		22	0.227	5.50	154	677
		25	0.207	4.50	119	579
		28	0.183	5.25	150	832
		31	0.185	5.17	169	913
		36	0.180	5.33	169	935
	Permanent	25	0.197	3.78	78	383
		28	0.265	3.67	88	334
		31	0.265	4.78	166	667
		36	0.273	5.55	195	704
		49	0.315	5.08	507	1674
Gladden	Seedling	9	0.222	3.44	98	445
		11	0.258	4.28	88	358
		13	0.217	4.89	96	436
		15	0.237	4.56	101	428
		17	0.228	4.06	107	476
		19	0.238	4.33	123	510
		22	0.187	4.67	143	753
		25	0.227	5.11	169	756
		28	0.215	4.67	169	791
		31	0.175	4.67	172	1012
		36	0.160	5.33	296	1853
	Permanent	25	0.287	2.52	63	221
		28	0.365	3.50	137	367
		31	0.335	4.00	149	482
		36	0.290	5.50	316	1083
		49	0.348	5.11	761	1457

Breaking tension increases in absolute value with maturity. The strength of even the seedling roots appears to increase very slowly up to the end of the experiment. These roots apparently continue to function, although growth slows down very much once the permanent roots are formed. The vascular core of permanent roots was relatively, as well as absolutely, larger than that of seedling roots. This is reflected in the more rapid increase in strength as the permanent roots mature and in a much higher maximum breaking tension.

Comparison of the behavior of the three varieties in this series with their behavior in the W and C Series is of considerable value, especially the breaking tension of the 49-day-old pot-grown plants with that of those grown outside. Table 15 presents the results both in absolute values and relative to Minhardi.

TABLE 15.—Breaking Tension of Roots of Three Winter Wheats in Three Series

Variety		Series W	Series C	Cornell Pot Series
Minhardi	Grams	246	304	537
	Per cent of Minhardi	100	100	100
Fulhio	Grams	386	479	507
	Per cent of Minhardi	157	157	94
Gladden	Grams	534	547	761
	Per cent of Minhardi	217	180	142

Growing conditions for these three series have already been discussed. The W Series represents the most adverse environment, the Pot Series the most favorable, and the C Series intermediate. The strength of the roots varied with conditions, but the relative breaking tension did not remain constant. Minhardi is apparently the first of these varieties to react to unfavorable environment with reduced rate of growth, and Gladden is the last. It must be remembered that the maximum growth possible under ideal conditions is different for these varieties. Minhardi plants are always smaller and have narrower leaves and a more spreading habit. Gladden makes slightly more growth than Fulhio. These differences are evident at all stages of growth. Thus, under any conditions Minhardi would not be expected to produce either as many or as strong roots as Gladden. Nevertheless, it is apparent from Table 15 that Minhardi is capable of developing roots with a high breaking tension, and the reason it falls so far behind Gladden and Fulhio in the field is its marked reaction to unfavorable growing conditions.

Another possible factor is the amount of growth made before the dormant period. If planted in the spring, most varieties fail to head, and vegetative growth stops after a time. If there is a definite limit to the amount of fall growth possible, it would be important. Klages (3), however, was able to grow many winter varieties to maturity in the greenhouse without any rest period, provided proper conditions of light and temperature were maintained. He concludes: "The rhythm in the development as ordinarily observed in the growth of winter wheat is an enforced rhythm. Low temperatures and low intensities of light constitute the limiting factors in the growth of winter wheat in autumn." If this is so, the rest period so commonly considered essential can be interpreted purely as a response to adverse environment and the cessation of growth of varieties at different stages as a simple extension of this response.

Taken as a whole, the evidence strongly indicates that response to adverse conditions differs with variety and that cold-resistant wheats cease growth before cold-susceptible. This latter observation is in agreement with the statement of Rosa (8): "Any treatment materially checking the growth of plants increases cold resistance."

RANKING VARIETIES ON WINTER BEHAVIOR

Interpretation of results is, of course, impossible without definite knowledge of winter behavior. For this reason, the varieties used in these studies were chosen from the planting list of the Eastern Uniform Winterhardiness Nursery, and selection was made to include wheats developed over a wide range of conditions and wheats adapted to widely varying conditions. Seed of the identical lines used in the nurseries was obtained, so that results could be compared.

Because there has been abnormally low rainfall over the northeastern United States for some years and this period has been characterized by low precipitation in winter and early spring, heaving damage has not occurred to any appreciable extent since the winterhardiness nurseries were established. Unfortunately from the point of view of this study, it has not been possible to rank varieties accurately in their resistance to heaving. This is particularly serious since, as was mentioned earlier, no careful study of varieties in regard to this characteristic has ever been made. Realizing that this difficulty might arise, in the summer of 1934 the author sent questionnaires to a number of experiment stations asking them to rank as many as possible of the 15 varieties used in this study in their resistance to winter injury when direct effects of low temperature were not the primary cause of damage. The questionnaire also asked what was the most prevalent cause of injury from the indirect effects of low temperature. Nine replies were received.

The answers emphasized the fact that opinions only were given and that there was no experimental evidence for the rankings. Heaving was indicated as by far the most common cause of injury, aside from cold. In regions of light textured and well-drained soils, heaving was of secondary or only occasional importance. West of Ohio, the ranking of varieties indicated that, though heaving was a factor, it was not the most important consideration. This was evident because of the high rank of Minhardi, Kharkov, and Purkof. The more southern states, with heavier soils, indicated heaving of prime importance and low temperatures directly as unimportant. Under these conditions, Purplestraw ranked well up in the list and Minhardi came last. Minhardi was dropped from the West Virginia variety test because it winterkilled so severely.

These generalities fit in well with the opinions of the author as to the types and causes of winter injury and the rank of varieties. In no field test of varieties has heaving been a factor of any importance in Ohio during the past 4 years and previous to that time the writer was not in the State. However, colleagues, farmers, and seed growers have indicated that heaving is a very common cause of injury and that Gladden is highly resistant to it. Nittany does better on the heavy soils of eastern Ohio than elsewhere in the State and heaving is worse on such soil types. Careful study of the wheat nurseries at various points in the State showed definitely that in a few cases Minhardi and Minturki had been slightly heaved from the ground when no other varieties had. Minhardi consistently was worst affected. When cold winters occurred, as in 1933-1934, these varieties showed least injury of all. Varieties such as Purplestraw, Leap, and Red Hart were severely damaged by low temperatures directly in these same winters.

In 1933-1934, injury from the direct effects of low temperature was so marked that, in the report on the Eastern Uniform Winterhardiness Nurseries for that year, Taylor (11) grouped varieties into classes according to their cold resistance. The varieties used in the present studies ranked as follows:

Excellent:	Minhardi, Purkof, Kharkov
Good:	Harvest Queen, Purdue No. 1
Fair:	Trumbull, Fulhio, Fulcaster, Poole, Nabob, Gladden, Nittany, Valprize, Red Rock
Poor:	Purplestraw

The Indiana Station has run cold chamber tests on these varieties, and Cutler (2) reports that in preliminary tests they ranked as follows (the most cold resistant in Class I):

Class I	Minhardi, Kharkov, Purkof
Class II	Purdue No. 1, Harvest Queen
Class III	Fulcaster, Gladden, Nabob
Class IV	Red Rock, Trumbull, Poole
Class V	Fulhio, Nittany, Valprize, Purplestraw

There is reasonably good agreement between these two rankings, indicating that injury in 1933-1934 was largely due to the direct effect of low temperatures.

Of fundamental importance is the ability of a winter wheat to resist the direct effects of low temperature, down to the minimum likely to occur in the region where it is grown. In addition, if heaving is a factor, the plants must be able to resist this also. The most cold-resistant varieties are not resistant to heaving. Some varieties resistant to heaving, such as Purplestraw, cannot stand even moderately low temperatures. Other varieties, such as Harvest Queen and Gladden, are reasonably resistant to both cold and heaving.

While ranking of varieties in order of resistance to heaving cannot be based upon actual experimental evidence, there are very strong indications that Gladden and Nittany are highly resistant but that Minhardi and Kharkov are distinctly susceptible to this type of injury. This fits in well with the assumption that vigorous-growing varieties with large and strong roots are most resistant to heaving damage. Such a ranking also fits in well with the theoretical considerations which will now be discussed.

It has been pointed out that heaving is a physical phenomenon occurring in soils under specific conditions and that damage to the crop results because the plants are pulled from the soil when the surface crust is thrust up by the separating out of ice layers below. It occurs when a saturated soil is frozen and water can move to the frozen layer under capillary forces. The amount of heaving that will occur is limited by the amount of heat lost by the soil. Vigorous well-grown plants provide a cover which has a marked effect on the rate of cooling of the soil. Furthermore, when sown in drills, wheat forms rows of plants with open spaces between. When leaves are killed back, they wither and form a protecting layer over the crowns of the plants. When the soil freezes, heat loss is much more rapid between the rows, and heaving may start before the crowns are firmly embedded in the surface soil. The more dense the foliage, the greater the protection of this type it can afford. Thus, it is seen that top growth as well as root growth may be a factor in resistance to heaving.

GENERAL SUMMARY AND CONCLUSIONS

The experiments reported here were designed to find characteristics of the roots of winter wheat varieties which might be associated with resistance to winter injury from soil heaving by frost. Two assumptions were made: first, that varieties differ in their ability to resist heaving injury, and, second, that the ability to resist such injury is primarily due to some properties of the roots. The first of these assumptions is borne out by the observations of a number of experiment station workers. Granted varietal differences do exist, it is difficult to conceive of the characteristics of top growth playing the dominating role in varietal behavior, although such can by no means be considered as without significance.

Kokkonen's work with rye in Finland, indicating the significance of root strength and stretching ability in resistance to winter injury, is very suggestive. Major emphasis was laid on these root characteristics in the investigations reported here, but a number of other factors have been studied.

Size of root, which may be related not only to strength but to resistance to desiccation as well, is a factor to be considered. Extensibility of roots varies among varieties, the more heaving resistant having the greater stretching capacity. This may be incidental, however, since all varieties appear to be able to stretch sufficiently to accommodate themselves to volume changes when soil freezes solid, and strength is probably much more important when heaving takes place.

Breaking tension of the root is very important, probably not so much because it is of an order sufficient to withstand heaving or prevent it but because it may be sufficient to prevent root breakage so near the surface when the crown is actually pulled up by frost action. In soils with very large capillary pores, where undercooling is only slight, strong roots may actually prevent the heaving up of the crown of the plant. The total force necessary to pull a plant from the soil should be studied.

Besides strength, other factors which may play a part in determining the reaction of a plant to heaving are the number and type of roots, whether they are profusely branched or not, and at what distance below the surface branching begins, as well as size of cells in the vascular tissue and the proportion of vascular system to cortex.

The tests run on plants grown at different fertility levels indicate that not only the total development but also the type of development may be influenced by the supply of plant nutrients and the ratios which exist among the elements, especially the available N, P, and K. It is evident that, in any case, well-developed, vigorous plants in the fall are essential to maximum resistance to spring heaving injury. Indications are that varieties differ markedly in their ability to continue growth at a relatively high rate as conditions become more and more adverse with the approach of winter. Cold-resistant wheats stop growth first; whereas those varieties most resistant to heaving continue to grow longest of all.

There is evident a definite antagonism between cold resistance and heaving resistance. However, there is no indication that, for Ohio conditions at least, a wheat cannot be developed that will have sufficient cold resistance to withstand any ordinary winter and at the same time be highly resistant to heaving. In fact, Gladden does not fall far short of this ideal. Somewhat greater cold resistance would be desirable, but over the State it has had an excellent record of survival during the past 20 years.

Purplestraw, well adapted farther south, lacks cold resistance when grown in Ohio. It has heaving resistance but lacks the ability to survive low temperatures and has found its place in the regions where wheat is seldom killed by cold. Leap and Red May probably belong to the same group. Minhardi and Kharkov stand at the opposite extreme, being very resistant to low temperatures but readily injured by heaving. These wheats are adapted to the Great Plains where the winter temperatures are severe, and heaving injury is practically non-existent because of the soil moisture conditions. The newer varieties, adapted to the region in which they were developed, have size and strength of root proportional to the probability of heaving damage, as indicated by weather data. Cold resistance is likewise sufficient for the particular location.

There was little precedent for these studies, and, as the work progressed, it became more and more evident that the technique was far from perfect. Care was taken to avoid any possible artificial groupings, with the result that errors are higher than would otherwise have been the case. When differences are indicated, however, they can be considered as of real significance.

Considered in this light, the studies reported here indicate clearly that certain root measurements vary markedly with variety and with the resistance of the variety to cold and to heaving injury. Observations combined with the results of the experiments further indicate that no one characteristic of the roots alone is an entirely satisfactory measure of ability to resist heaving and that a number of attributes not studied as yet may have considerable significance in determining behavior. The environment in which the wheat develops in the fall, both as regards soil and climate, has a profound influence on the degree of resistance to heaving. Varietal differences are largely independent of environment. The combination of resistant variety and favorable fall environment is essential to reduction of injury from heaving to a practical minimum.

The results so far obtained justify further work. A more detailed study of certain root characteristics, combined with further investigation of the phenomenon of heaving, may lead to an empirical test which will give accurate information on the resistance of new lines of wheat to heaving damage. The studies reported here have served their purpose and have given needed information as to the lines along which further work should be planned.

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